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QUARTERLY REPORT ON THERMAL AND ELECTRICAL CONDUCTIVITIES OF BIOLOGICAL FLUIDS AND TISSUES

ONR CONTRACT NO. 4095(00), A-1

Period

April 1 to June 30, 1964

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SUMMARY

This report describes Geoscience's research on thermal and electrical conductivities of biological fluids and tissues for the Medicine and Dentistry Branch of the Office of Naval Research (Contract No. 4095(00), A-1) for the period April 1 to June 30, 1964.

Experimental electrical conductivities of human gastric juices, urine and bovine aqueous and vitrious humours were determined. A special cell for the determination of electrical conductivities for tissues has been designed, constructed, and tested. Experimental measurements of the electrical conductivity of cow blood was determined as a function of hemolysis.

A modified thermal conductivity apparatus was used to measure the conductivities of beef lung, liver, kidney, brain and chicken skin. Thermal conductivity correlation expressions for biological fluids and tissues are evaluated.

CONTENTS

I. ELECTRICAL CONDUCTIVITY

A. Biological Fluids

The electrical conductivities of human gastric juices, urine and bovine aqueous and vitrious humours were determined. These data are compared graphically in Figure 1 with representative values for human blood plasma. It may be noted that within the accuracy of the conductivity bridge ($\pm$ 0.10%), values for the aqueous and vitrious humours were identical. In vew of the great difference in viscosities (a factor of 15-20) between the two latter fluids, it may be assumed that the vitrious humour possesses a higher compensating ionic concentration than the aqueous humour.

The conductivity studies to date have shown urine to be the most highly conducting biological fluid.

B. Biological Tissues

A special cell for the determination of the electrical conductivities of biological tissues has been designed, constructed and tested. The cell, shown in Figure 2, has been designed for use with the precision conductivity bridge or the standard potential-current (4 electrode) technique. Using both methods, data can be obtained to evaluate the extent of possible electrode interface resistance, or polarization errors. Both platinum electrode surfaces in contact with the biological tissues will also be platinized to reduce polarization errors.

C. Blood

Present efforts in blood plasma conductivity research are being directed toward the establishment of a correlation between plasma conductivity and hemolysis (gram % hemoglobin). As described in the previous report[1], the total gram percentage of hemoglobin in the plasma is measured by the cyanmethemoglobin technique. A lengthy series of conductivity determinations of cow blood plasma containing varying amounts of hemoglobin was made between 26°C and 46°C. These data are shown in Figure 3 plotted versus temperature with gram percentage hemoglobin content as the parameter. A more useful presentation of the data for 28°C may be seen in Figure 4 where the dimensionless conductivity ratio K/K_o is plotted against hemolysis values.

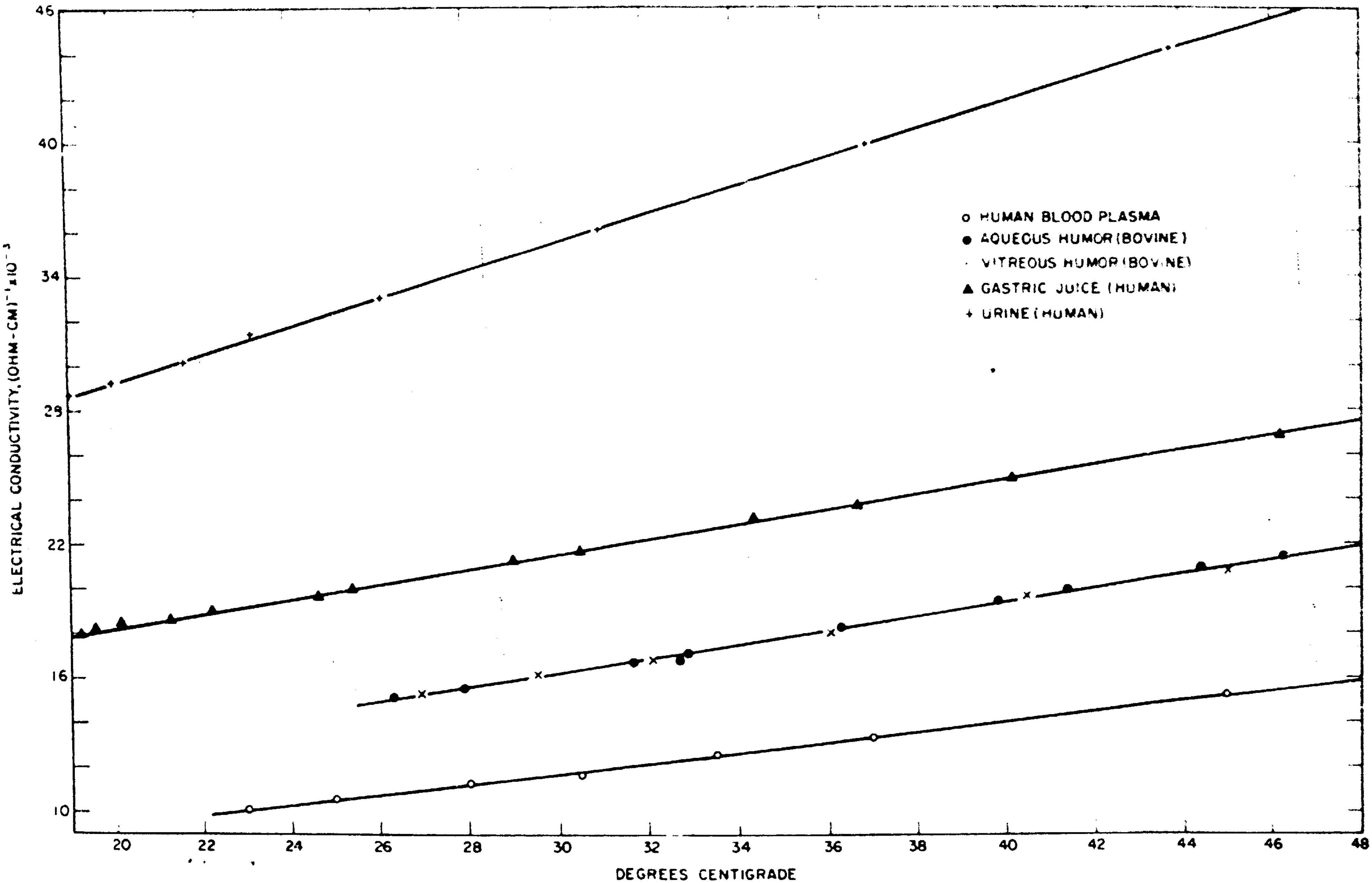

Figure 1. A summary of the electrical conductivities of several biological fluids.

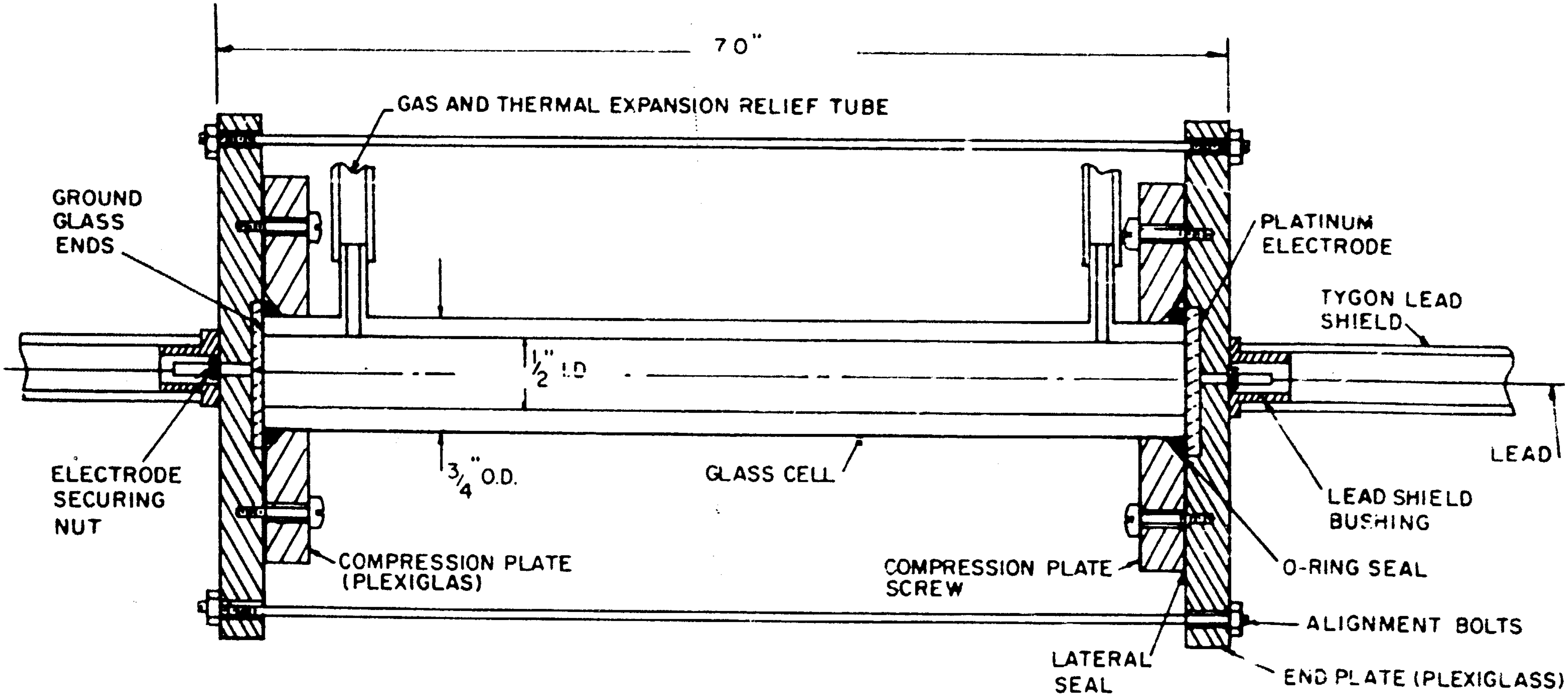

Figure 2. The biological tissues conductivity cell.

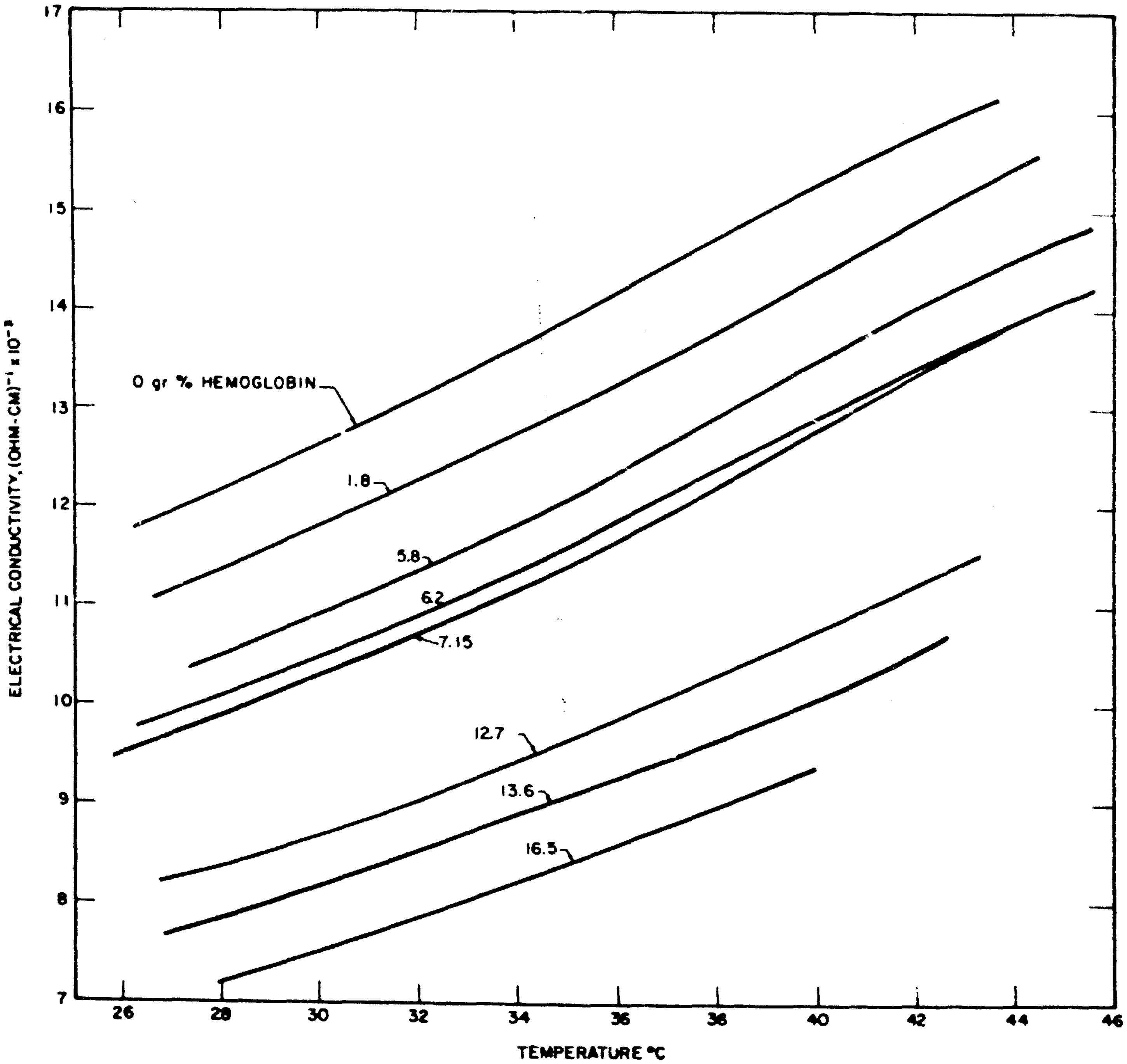

Figure 3. Electrical conductivity of bovine blood plasma with temperature.

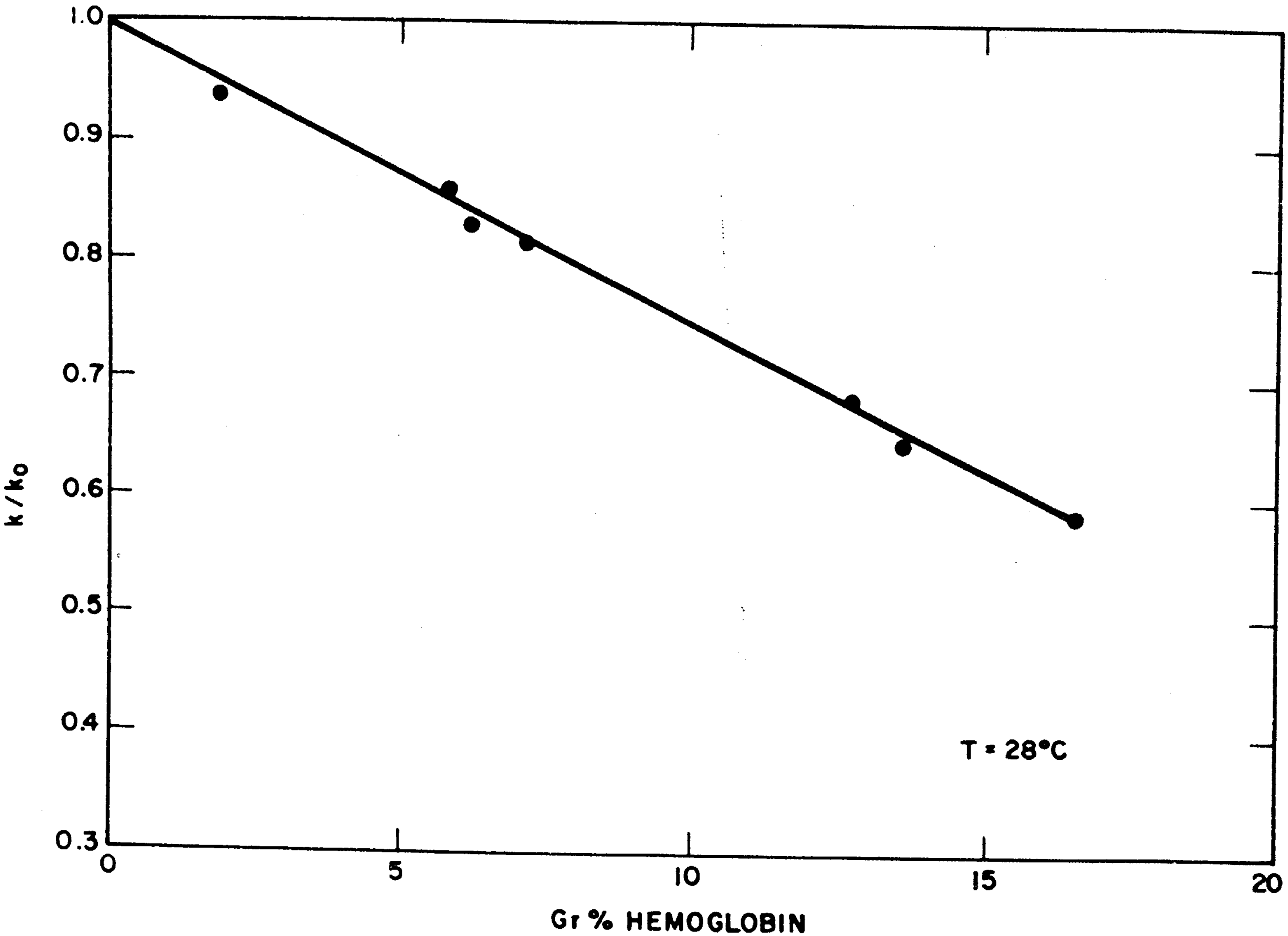

Figure 4. Dimensionless conductivity versus gram percentage hemoglobin content in bovine plasma.

The value K_o denotes the basic conductivity of the plasma with no hemoglobin present (before damage). This general curve can then be used to ascertain the hemolysis of blood knowing electrical conductivity values.

II. THERMAL CONDUCTIVITY

A. Biological Tissues

The apparatus previously used for measuring the thermal conductivities of biological tissues and fluids[1] was modified somewhat before the current data were collected. Changes were made in the heating circuit; two flat electrical heating elements were used and a null heat meter inserted between them (see Figure 5). The electric powers for the two heaters were so adjusted that the heat flow through the null heat meter was zero; under these circumstances, the heat generated in the bottom heater was forced to flow through the cell containing the biological specimens. A piece of insulating material was placed between the top heater and the cooling plate to keep the current-voltage requirement of the top heater at a minimum. Spacers were added to the plastic insulation around the cell to insure correct positioning of the lower heating element. Because of the small difference in temperature between the cell and the container environment, the heat loss from the cell ends was small. The thermal conductivity cell itself consists of two highly conducting plates containing embedded thermocouples. These plates are spaced a short distance apart to maintain a large width to thickness ratio and thus insure one-dimensional heat flow through the cell.

The thermal conductivity apparatus was used to measure the conductivities of beef lung, liver, kidney, brain and chicken skin. Measurements of the conductivity of distilled water were made periodically to check the accuracy of the system; all measurements for water were within $\pm 3\%$ of the established values. The thermal conductivities of unstressed biological tissues obtained in the current study are reported in Table 1, together with results of previous experimentation using this equipment.

B. Thermal Conductivity Correlations

Attempts have been made to establish a correlation between the thermal conductivities of biological materials and another of their physical properties. Spells[2] has proposed that a correlation exists between water content and thermal conductivity.

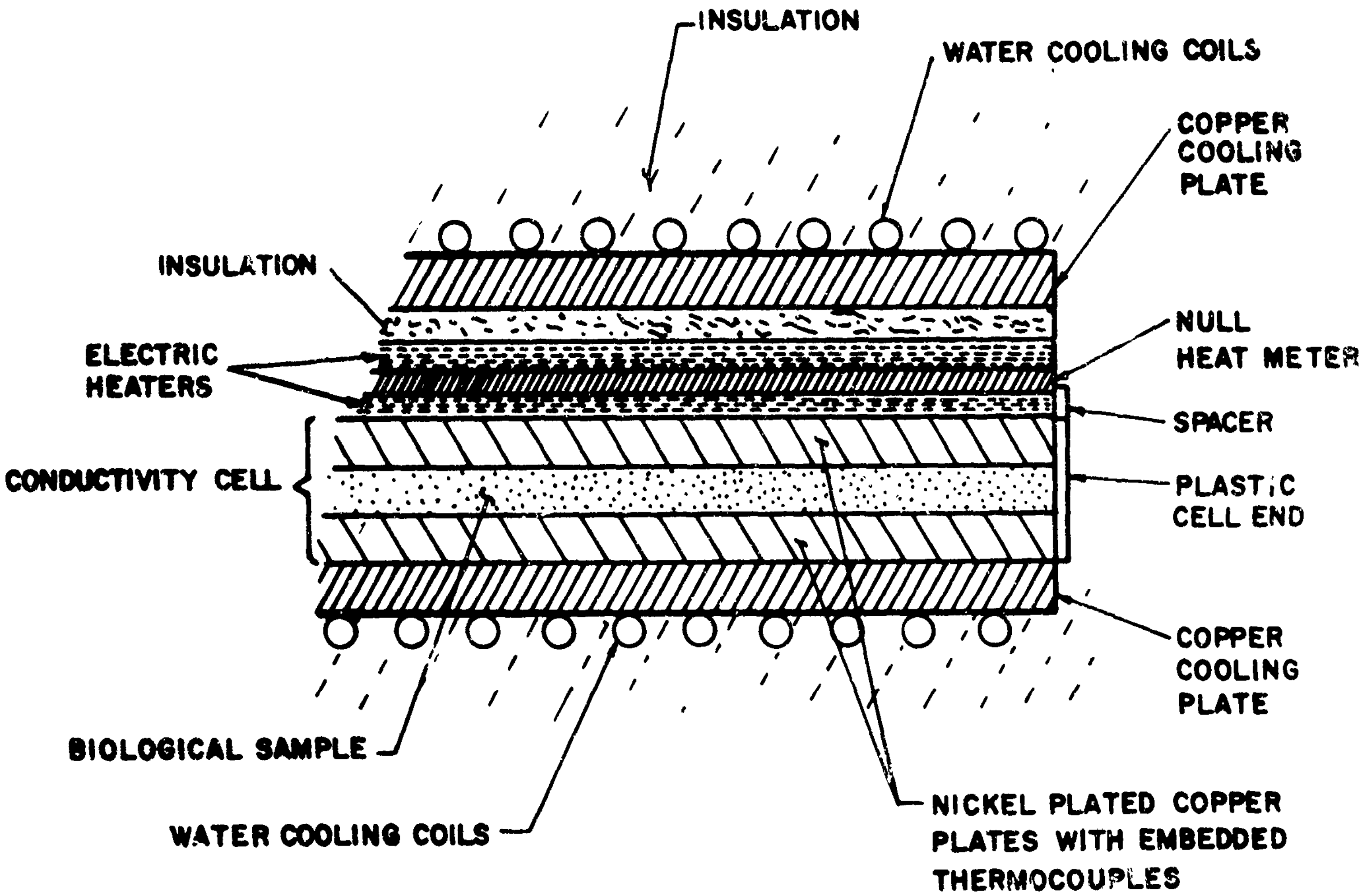

Figure 5. Cross sectional view of thermal conductivity cell.

Table 1. Thermal conductivity of unstressed biological fluids and tissues ($75°F < t < 100°F$)

Sample	Thermal Conductivity Btu/hr ft°F
Water	0.350
Plasma*	0.330
Urine*	0.324
Blood (hematocrit = 43%)*	0.306
Beef Muscle*	0.305
Beef Kidney	0.303
Beef Brain	0.287
Beef Liver	0.282
Gastric Juice*	0.257
Chicken Skin	0.206
Beef Lung	0.163

*From previous results reported in the Quarterly Report on Thermal and Electrical Conductivities of Biological Fluids and Tissues, GLR-28, April 1 - June 30, 1964.

For the materials which he included in his study, the correlation seemed to hold for samples with a water content of 50% or higher. When several additional biological materials were examined in the current study, however, and their thermal conductivities were plotted versus water content, the linear correlation was no longer found to hold. The most notable deviations occur for gastric juice, chicken skin and beef lung, samples with water contents greater than 70% (see Figure 6). Table 2 lists the values appearing in Figure 6 and the sources from which these values were obtained. Thus the water content correlation does not appear to be valid in a general sense. It is nevertheless a useful guide for estimating the thermal conductivity of biological materials.

The following are suggested correlations for the thermal conductivity data now being investigated:

1. A molecular size or molecular weight relationship with thermal conductivity.

2. A relationship between the thermal conductivity of the biological specimen and the thermal conductivity of the individual species present.

3. A relationship between the speed of sound, moleculer spacing and the thermal conductivity.

The water content correlation would not be expected to be general. Consider the case of lung tissue. In this specimen there exists a large volume of captured gas. Since the thermal conductivity of gases is considerably smaller than that for solids and liquids, this accumulation of gas must contribute to the low value of thermal conductivity obtained for lung tissue. It thus supports the idea that not only water content, but content of all major species is important in correlating thermal conductivity values of various samples.

Bridgeman[6] derived a simplified expression which relates the thermal conductivity to the velocity of sound and the molecular spacing. Therefore, it may be possible to describe the thermal conductivity of biological materials in terms of the bulk modulus or compressibility and the density.

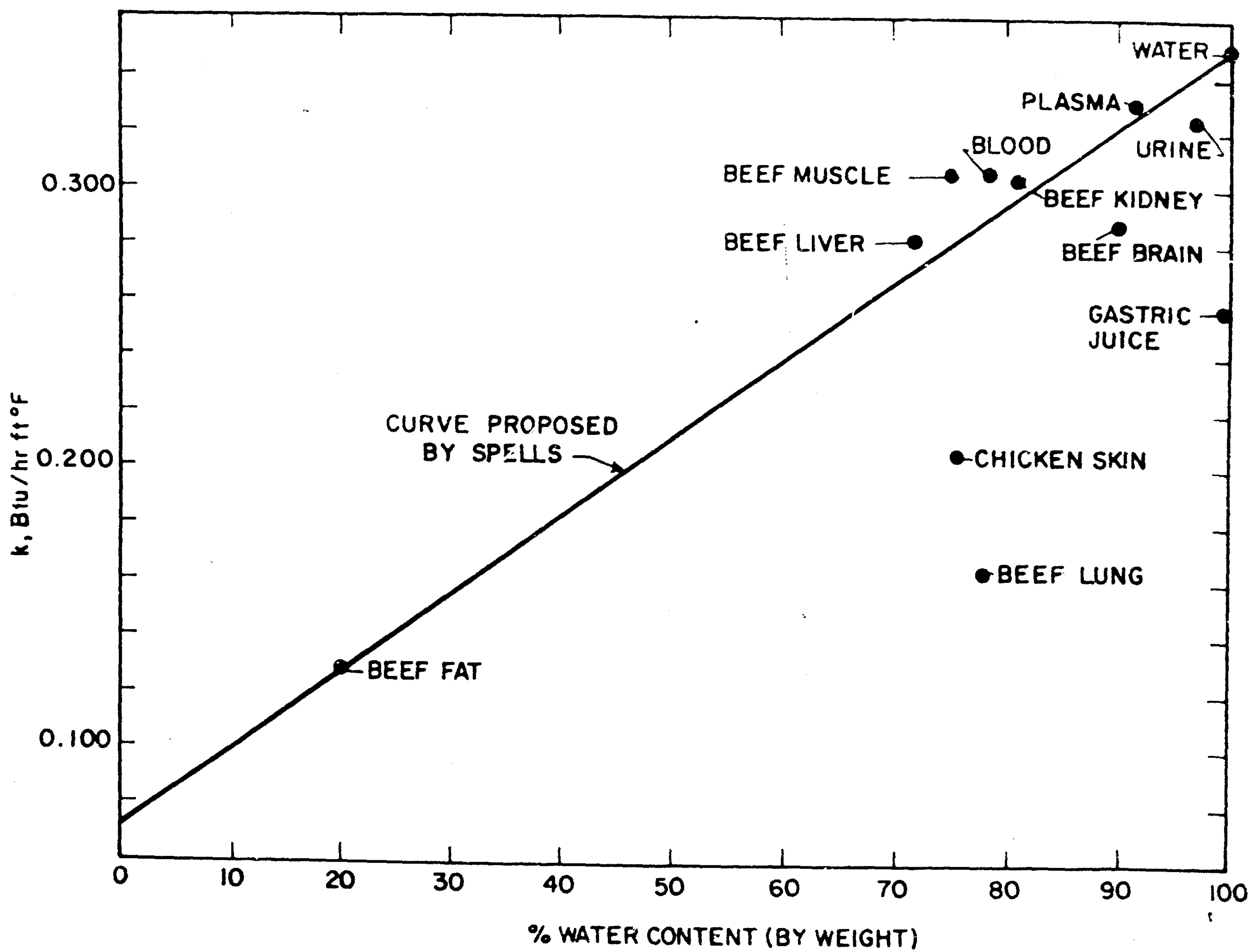

Figure 6. Thermal conductivity versus water content of biological tissues and fluids.

Table 2. Water Content and Thermal Conductivity of Biological Samples

Sample	$k_{experimental}$*	% Water †	Source for % Water Content
Water	0.350	100.00	--
Human Plasma*	0.330	91.5 (human)	Spells[2]
Human urine	0.324	97.0 (human)	Langley & Cheraskin[4]
Human blood* (hematocrit = 43 %)	0.306	78.5 (human)	Spells
Beef muscle*	0.305	75.0 (human)	Spells
Beef kidney*	0.303	81.0 (rabbit)	Spells
Beef brain	0.287	90.0 (human	Documenta Geigy[5]
Beef liver*	0.282	72.0 (rabbit)	Spells
Human Gastric juice	0.257	99.5 (human)	Stuhlman[3]
Chicken skin	0.206	73.0 (human)	Documenta Geigy
Beef lung	0.163	78.0 (human)	Documenta Geigy
Beef fat	0.128	20.0 (human)	Spells

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*All experimental values with the exception of beef fat were measured at Geoscience; the beef fat value was determined by Spells.

†It was not possible to obtain water contents for the exact specimens reported in the thermal conductivity column. Values for similar types of specimens are presented in this column.

C. New Thermal Conductivity Cell

A new thermal conductivity cell which represents a more compact device than the previous one has been designed and fabricated. A heater is mounted directly on the flat cell. The cell plates contain thermocouple holes which make it possible to remove and interchange thermocouples.

III. CRYOGENIC EXPERIMENTS

A number of preliminary cryogenic experiments were conducted in which biological fluids and tissues were frozen rapidly. All freezing studies were made using a liquid nitrogen. Samples of blood contained in metal cells and metal and glass capillary tubes were also immersed in the cryogenic fluid. Some quantitative information on the freezing and thawing rates have already been obtained.

IV. STUDIES TO BE PURSUED DURING THE NEXT QUARTER

1. Investigate the effect of specimen geometry on rapid freezing and thawing rates.
2. Ascertain the effect of the rates of freezing and thawing on hemolysis.
3. Investigate several of the proposed thermal conductivity correlations for biological fluids and tissues.
4. Measure the electrical and thermal conductivity of biological fluids and tissues that have been exposed to cryogenic environments.
5. Electrical conductivity measurements will be made in the low hemolysis (plasma-hemoglobin) range.

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